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Small-x final states and the CCFM equation*†

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Abstract: The status of the Milan group's work on CCFM-based phenomenology at small x, and possible directions of future investigation, are discussed.

In order to study final states in QCD it is generally necessary to take into account the coherence of QCD radiation [1]. At small x, coherence is embodied in the CCFM equation [2]. In [3] a first analysis of the CCFM equation was carried out with regard to small-x phenomenology at HERA. The information gained was to have served as a basis for a CCFM-based Monte Carlo event generator. The main results are summarised here, together with some discussion of possible future work.

As a first step, we studied the freedom available in implementing the CCFM equation, and noted that the non-Sudakov form factor (which resums virtual corrections at small x) is not uniquely defined. There are two possible choices for it. One leads to small NLL corrections compared to BFKL [4, 5], the other to large NLL corrections (much bigger that the true NLL corrections to BFKL).

Soft emissions (those from the $1/(1-z)$ part of the splitting function) were neglected throughout the analysis. Formally this should have been acceptable for the observables we considered. Their inclusion would have been another source of NLL corrections.

As a phenomenological constraint on the free parameters of our evolution we fitted the small-x F_2 structure function [6]. It was found that of the two possible implementations of the non-Sudakov form factor, only the one with the large corrections was able to reproduce the F_2 data. We then examined other, more exclusive, observables such as the transverse energy flow [7], charged-particle transverse-momentum spectra [8] and the forward-jet cross section [9, 10]. No hadronisation was implemented. Nor did we include the contribution to the final state from the quark box.

All final-state observables were systematically low (especially the E_t flow and the forward-jet cross section, which were off by a factor of 2). In the case of the E_t flow this might be explainable by the absence of the contributions from soft emissions and hadronisation corrections. Less so for the other observables. As an example, figure 1 shows our results for the forward-jet cross section, together with an indication of the uncertainties, as compared to the data.

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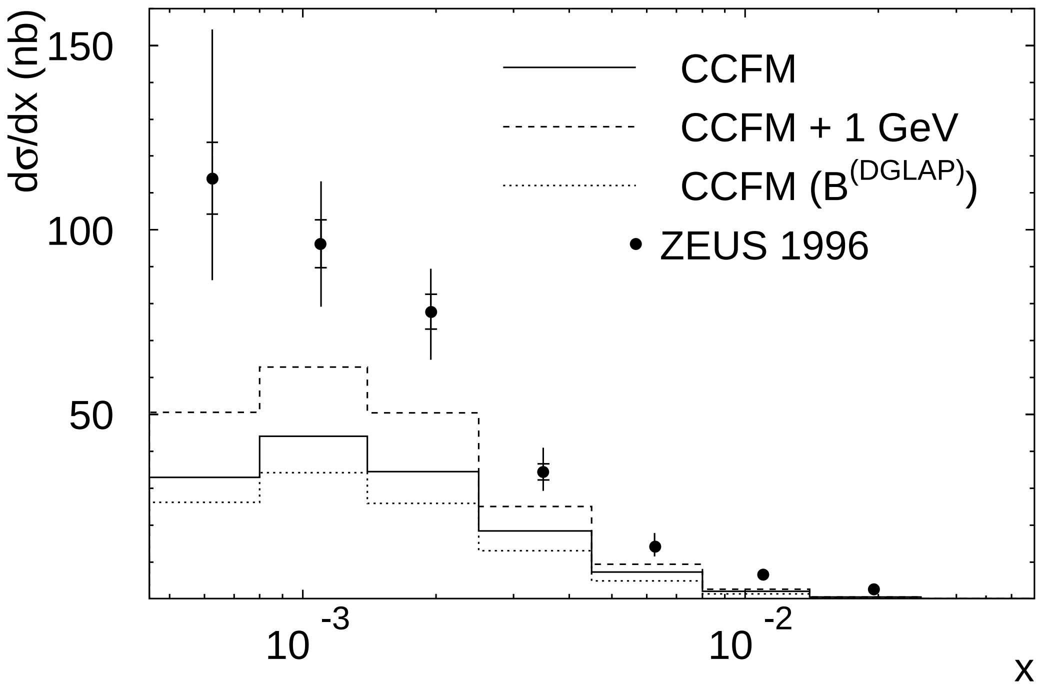

Figure 1: Forward-jet cross section from [3] as compared to ZEUS data [9]. The differences between the three histograms are indicative of the uncertainty on the theoretical result.

What is our understanding as to why we failed to reproduce the data? We suspect that the choice of implementation of the non-Sudakov form factor is largely to blame. We needed a 'source of subleading corrections' in order to be able to fit F_2. This was given to us by our modification of the non-Sudakov form factor. But we subsequently discovered that this modification leads to strange behaviours, such as small-x cross sections (e.g. for forward jets) which first decrease as x decreases, and only at very small x start to increase: our source of subleading corrections was too large and had the wrong characteristics.

Does this mean that the CCFM equation is inconsistent with the data? Not necessarily. It should be remembered that we did not include the soft emissions. It is quite possible that they alone would have been a sufficient source of subleading corrections, in order to allow a fit to the structure function data, without requiring a modification of the non-Sudakov form factor (the soft emissions lead to somewhat smaller, but still sizeable NLL corrections). They would also have increased activity in the final state. Such an approach might therefore have led to much better agreement with the data. (This would have been close in physics content to the SMALLX [11] program, which is currently being studied by Hannes Jung [12], who finds that it does actually reproduce a range of data relatively well).

We have not however taken the seemingly logical step of implementing the soft emissions within our approach. Why? Two practical issues are involved. One is undoubtedly the difficulty involved — the inclusion of soft emissions complicates enormously the numerical solution of the CCFM equation.‡ Additionally, as mentioned above, there is already a program in existence, SMALLX, which implements CCFM including soft emissions. There, the difficulty of

‡It should be pointed out that the recent results on the LL equivalence of CCFM (including soft emissions) and BFKL final states [13] is not sufficient to allow one to use the BFKL equation as the basis of a Monte Carlo — indeed as discussed in [14], at subleading orders, in DIS, the BFKL equation has serious pathologies in its final states.

implementing soft emissions is traded for difficulties of use (it is a forward-evolution Monte Carlo generating weighted events, with considerable fluctuations in the weights), and restricted flexibility in certain areas such as the inclusion of the appropriate scale for the running coupling.

But there are also physics issues of relevance. In the past year the NLL BFKL corrections have become available [5] and there has been significant progress in understanding the physical origins of the numerically dominant parts of the corrections [15]. The CCFM equation (even with soft emissions and running coupling) is missing two of the main physical parts of the NLL corrections. There is a contribution related to the finite part of the gluon splitting function (while the $z \to 0$ and $z \to 1$ singular parts are included by the CCFM equation, the part which is finite at both $z = 0$ and $z = 1$ is not). This might be quite straightforwardly included in the CCFM equation. But there is also a component of the NLL corrections which ensures the symmetry of the evolution — the requirement that evolution from a small (transverse) scale to a large scale give the same answer as evolution from a large scale to a small scale. The CCFM equation does not satisfy this symmetry, corresponding technically to the absence of the component of the NLL corrections which goes as $1/(1-\gamma)^3$ (γ is the Mellin transform variable conjugate to the transverse momentum). Nor is it immediately clear how to introduce this symmetry without modifying the whole structure of the CCFM equation. (Such a modification has been proposed, in the form of the LDC model [16], but it changes the small-x leading logarithms).

Given that without these contributions, in terms of the physics included, it would be difficult to improve significantly over the already-existing SMALLX program, we have decided to place on hold our plans for the construction of a small-x Monte Carlo event generator. Such a project is of considerable importance. But an important (and ongoing) part of it is to understand how to include the various physical components of the NLL corrections outlined above, into an equation such as the CCFM equation which is suitable for final-state studies.

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